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A Review on Flexible Substrate Materials for Stretchable Electronic Devices

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ABSTRACT

Stretchable electronic devices have exerted an overt impact on developments in wearable electronics, biomedical devices, soft robotics and the Internet of Things (IoT), with flexible substrate materials playing a fundamental role as building blocks. This extensive study provides a detailed comparison and contrast of the properties (mechanical, electrical, environmental) of polymer-based, organic compounds, bio-based materials as well as hybrids as substrates for stretchable electronics. Polymer substrates like polydimethylsiloxone (PDMS) and polyurethane have made it possible to obtain stretchability (150%-200%) along with biocompatibility, crucial for making wearable sensors or implants with sensitivity down to 0.5 kPa^{-1} Biodegradability within 30 days makes organic substrates such as cellulose and silk part of the sustainable materials that derived functional properties, suitable for disposable biosensors. The graphene /silver nanowires hybrid substrates exhibit relatively low sheet resistance (10 Ω/sq) and high transmittance (89%), which is well suited for stretchable circuits and displays. Scalability is further supported by spin-coating, 3D printing, and roll-to-roll processing techniques but uniformity as well as cost remains into question. Key limitations include mechanical fatigue (typically 10,000 cycles), conductivity decrease under flexion, high processing costs ($50–100/kg for organic substrates) and regulatory challenges in the biomedical field. The review focuses on novel trends such as self-healing polymers which recover up to 90% of mechanical properties and bio-inspired substrates for enhanced biocompatibility. Future work, which targets at low-cost and easy scale-up of nanomaterial synthesis, 4D printing for dynamic structures, and integrating with AI/IoT to realize intelligent devices (50 μW/cm²), is also discussed. This work revisits the studies of substrates, as well as actives and passives in other works to present an all-embracing view regarding the substrate materials, applications, and challenges that subsequently helps in paving the way for sustainable scalability of stretchable electronics.

KEYWORDS

Flexible substrates; Stretchable electronics; Wearable devices; Biomedical implants; Soft robotics; Sustainable materials

1. INTRODUCTION

Stretchable electronic devices represent a transformative frontier in modern technology to enable applications that require the properties of flexibility, conformability and also withstanding damage through mechanical deformation. Stretchable systems can bend, twist and stretch over various surfaces and are perfect for wearable platforms such as electronic skin, implantable biodevices, soft robotics, human-machine interfaces (HMIs), etc. unlike conventional rigid electronics [1]. Adhering to the growing need of advancements in healthcare and consumer electronics, global market for flexible/stretchable electronics are expected to have an eye-catching growth [2]. Flexible substrate materials serve as the mechanical and electrical foundation for embedding conductive elements, sensors, and circuits in these devices. In this review, we highlight the development of flexible

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substrate materials by focusing on their properties and introduction to different fabrication techniques alongside applications, challenges.

Due to the demand for desired stretchability and biocompatibility, as well as durability, flexible substrates, such as polymers (e.g., polydimethylsiloxane (PDMS), polyurethane), organic biomaterials (e.g., cellulose, silk) [4], and hybrid composites (e.g., graphene-reinforced polymer) are key components of IBTs [5]. More broadly, these materials must bridge the gap between mechanical properties (i.e. elasticity and tensile strength) and electrical performance (conductivity under strain), needs that were identified at the outset for skin [4] or displays on deformable surfaces. For example, PDMS is predominantly used domestically for it´s excellent stretchability and biocompatibility, making it most appropriate for wearable sensors [5]. However, the evolution of materials such as bio-based substrates has provided sustainable solutions for electronics manufacturing thus meeting nature-compatibility concerns [6]. More recent developments have also seen self-healing and nanomaterial-reinforced substrates to improve the durability and efficiency of a device [7].

These advances notwithstanding, the challenges associated with the realization of scalable, high-performance and low-cost growth substrates are enormous. However, the bulk commercialization of these actuators is difficult because mechanical fatigue always takes place under repeated stretching, conductivities in hybrid systems are somewhat limited, and especially production costs are too high [8]. Furthermore, the integration of flexible substrates with rigid components (e.g., microchips) represents a compatibility issue [9]. It is essential to tackle these issues for enabling the burgeoning applications of stretchable electronics either in internet of things (IoT) or biomedical diagnostics.

In this review, flexible substrate materials with respect to stretchable electronic devices are extensively covered by thoroughly analyzing their properties, fabrication methods, and applications as well as limitations. It synthesizes some of the latest literature, revealing trends, e.g., on sustainable and bio-inspired materials (firmly entrenched within our toolbox), and gaps or opportunities for further work.

2. RELATED WORK

The burgeoning growth in the field of stretchable electronic devices has encouraged numerous investigations into flexible substrate materials which are crucial for realizing mechanical flexibility, electrical performance, biocompatibility, and sustainability for a wide range of applications such as wearable electronics, biomedical devices, soft robotics, flexible displays, and the internet-of-things (IoT). Such substrates, of polymer-based materials (illustratively polydimethylsiloxane, PDMS; polyurethane, PU), organic and bio-based materials (cellulose, silk) and hybrid composites (graphene-PDMS, silver nanowire-, AgNW-, PDMS), provide devices capturing dynamic surfaces that endure sustained mechanical strain21. In the last five years (2020–2025), notable improvements on electronic functionalities have been achieved with respect to substrate stretchability (up to 200%), electrical corrosivity (<10 Ω sq), and environmental endurance (e.g., 30-day degradation for cellulose). In addition, research has been geared toward novel fabrication methods such as kirigami based designs and R2R (roll-to-roll) processing to make them scalable and cost-competitive. But most previous work has treated the active components, such as transistors or sensors, rather than the substrates themselves, which are crucial for mechanical, electrical, and ecological considerations and can cinch how readily a new technology might be scaled up for commercial production. It fills the gaps by an in-depth review of polymer, organic, bio-based and hybrid substrates properties, fabrication methods as well as applications and challenges with focus on sustainability, scalability and performance trade-offs to guide future researches in stretchable electronics.

2.1. Polymer-Based Substrates

Commonly, polymer-based substrates such as PDMS, PU, and polyimide are used to stretchable electronics because of their flexibility and feasibility fabrication. PDMS-only based flexible elastic substrates have been developed for use as a wearable type sensor exhibiting up to 150% strain on the elastically-deformed biocompatible substrates suitable especially for e-skin technology [5]. Biomedical implantable PU substrates with tensile strength pursuing 10 MPa and elongation exceeding 200% are suitable for dynamic applications like cardiac monitoring systems [10]. Polyimide substrates, which have been known for their thermal stability and can be used in flexible display technologies, but the limited stretchability (less than 50%) constrains its application when high deformation is required [11]. Modern researches have utilized self-healing polymers to enhance the life of cyclic durability in electromechanical action yet the obstacles, as discussed, in maintaining electrical activity continue to be tremendous. Despite such progress, polymer substrates repeatedly suffer from low-conductivity, except when combined with conductive additives, hence growing investigation about hybrid material systems.

2.2. Organic and Bio-Based Substrates

The increasing demand for environmentally-friendly electronics has driven research on earth-abundant materials such as recyclable plastics and bio-materials, including cellulose and silk-based substrates. Samples completely degraded in 30 days and exhibited tensile strengths of around 5 MPa, suggesting that cellulose-derived substrates are strong enough for use in single-use sensing applications, making them among the most viable candidates for sustainable electronics due to their low weight and environmental benignity. Silk-formulated substrates offer biocompatibility and biodegradability essential for implanted medical devices, and when employed with thin-film transistor integration can achieve 100% extensibility; however, scalability in manufacturing remains constrained due to intricate fabrication steps [12]. The fatigue resistance of natural rubber, functioning as an eco-friendly substrate, reaches 200 J/m², four times higher than that of hydrogel materials, demonstrating its feasibility for energy-collection applications [13]. Still, compared to synthetic polymers, many organic substrate materials possess relatively poor mechanical strength, which hinders their use in high-stress environments.

2.3. Hybrid and Composite Substrates

Hybrid substrates, which combine polymers with nanomaterials like graphene, CNT or metal nanowires, address limitations of conductivity and mechanical robustness. Graphene-reinforced PDMS substrates have been fabricated with a sheet resistance of <10 Ω/sq and stretchability up to 120%, making them suitable for flexible circuits [5]. It has been shown that nanomaterial dispersion plays a major role in maintaining electrical stability under strain. Flexible sensors using CNT-polymer composites achieve improved tensile strength (15 MPa) and maintain conductivity under 100% strain [14]. Hybrid substrates for stretchable displays, such as silver nanowire (AgNW)-polymer composites, combine ≥89% transparency with low sheet resistance, making them critical for active-matrix organic light-emitting diode (AMOLED) displays [15]. Metal-oxide-polymer composites, integrating inorganic and organic elements, enable ultra-high device density for bio-integrated systems [16]. However, long-term reliability remains challenged by issues like nanomaterial detachment during cyclic deformation.

2.4. Fabrication and Structural Innovations

More recent literature has also focused on improving the performance of substrates through new fabrication techniques and structural designs. A PU substrate microcracked conductive thin-film platform has been developed, achieving >150% stretchability and conductivity comparable to rigid

electrodes [12]. Scalable methods like 3D printing and roll-to-roll processing have been explored, though challenges with uniform thickness and cost persist [17]. Structural strategies such as origami and kirigami designs enable inherently non-stretchable materials like silicon to act as flexible substrates, opening new possibilities for high-performance electronics [18]. These developments emphasize the necessity of large-scale production routes that are not cost-prohibitive.

Various reviews have reported on flexible electrodes and their applications, most of which focus on active components, while the literature lacks an in-depth examination of substrate materials. At present, no complete comparison exists of the mechanical, electrical, and environmental parameters for polymer, organic, and hybrid substrates. Furthermore, few studies explore the recycling of sustainable materials and their potential scale-up for mass production. While some recent advances in self-healing and bio-inspired substrates are available in the literature, a consolidated review is greatly needed. This review aims to fill this gap by conducting a systematic evaluation of flexible substrate materials, their manufacturing processes, applications, and challenges, with a focus on recent advances and sustainable approaches.

3. FLEXIBLE SUBSTRATE MATERIALS

Flexible substrates are a critical platform for stretchable electronic devices that must deliver mechanical flexibility, strong electrical performance, and biocompatibility, while also supporting sustainability goals. They are essential in applications such as wearable electronics, biomedical implants, soft robotics, flexible displays, and Internet of Things (IoT) devices. These materials must combine high stretchability, durability, and compatibility with conductive elements, alongside meeting specific criteria like biocompatibility for implants, optical transparency for displays, or environmental sustainability for green electronics. This section reviews three main categories, polymer-based, organic and bio-based, and hybrid and composite substrates, covering their properties, applications, recent advancements, fabrication challenges, and scalability. A comparative analysis is presented to guide material selection, emphasizing the trade-offs in mechanical, electrical, and environmental performance that are most critical for stretchable electronics.

3.1. Polymer-Based Substrates

Stretchable electronics are dominated by elastomeric polymer substrates such as polydimethylsiloxane (PDMS), polyurethane (PU), and polyimide (PI) due to their excellent elasticity, deformability, processability, and cost-effectiveness. PDMS, a silicone-based elastomer, exhibits high stretchability (>150%) and biocompatibility, making it an ideal candidate for wearable sensors and electronic skin (e-skin) technologies [15]. It offers a Young's modulus of 0.5–2 MPa, a sensitivity of 0.5 kPa^{-1} for real-time health monitoring in applications like fitness trackers and smartwatches, and a rapid response time of <0.1 s. PU provides superior toughness and stretchability (>200%) with a tensile strength of ~10 MPa, supporting biomedical implants such as cardiac sensors capable of enduring over 15,000 strain cycles without degradation. Polyimide, with thermal stability up to 300 °C, is widely used in flexible displays, but its limited strain capacity (<50%) restricts its role in highly dynamic applications [16]. Recent advances include self-healing PDMS variants capable of restoring 90% of mechanical properties after damage; however, their electrical performance under cyclic strain declines due to the instability of conductive fillers like carbon nanotubes (CNTs) or metal particles. Since these polymers require conductive additives to achieve electrical functionality, fabrication becomes more complex, driving the development of hybrid systems to overcome conductivity limitations.

3.2. Organic and Bio-Based Substrates

These substrates may be organic or bio-based, such as cellulose, silk, and natural rubber, and are increasingly utilized for their sustainability and biocompatibility, aligning with green electronics principles to address environmental concerns in manufacturing. Cellulose-based substrates, derived from plant fibers, are lightweight, biodegradable, and cost-effective ($20–50/kg), with tensile strengths of 5–7 MPa and stretchability in the range of 10–20%. Cellulose nanofiber films biodegrade within 30 days under physiological conditions, making them well-suited for disposable biosensors in applications like air quality monitoring. Silk fibroin, a natural protein, offers biocompatibility and moderate elasticity (up to 100%), supporting implantable devices such as neural interfaces. With a dielectric constant of 3.5, silk substrates achieve signal-to-noise ratios above 20 dB for brain signal monitoring in epilepsy diagnostics. Natural rubber demonstrates a fatigue threshold of 200 J/m²—over four times higher than hydrogels—enabling energy-harvesting wearables like self-powered fitness bands. However, organic substrates often lack mechanical robustness, with cellulose prone to tearing under high strain and silk requiring complex processing. Recent strategies, such as chemical cross-linking, aim to improve durability, but scalability is hindered by high production costs and sensitivity to environmental factors like humidity-induced degradation.

3.3. Hybrid and Composite Substrates

Hybrid and composite substrates combine polymers with nanomaterials such as graphene, CNTs, or AgNWs to enhance both electrical and mechanical properties. Graphene-reinforced PDMS substrates achieve sheet resistance below 10 Ω/sq and stretchability up to 120%, making them suitable for stretchable circuits in IoT sensors for smart cities. CNT–polymer composites offer tensile strengths of 15 MPa and maintain stable conductivity under 100% strain, which is advantageous for flexible robotics sensors [15]. AgNW–PDMS composites, with ≥89% transparency and <10 Ω/sq sheet resistance, are applied in stretchable AMOLED displays, enabling foldable smartphone screens with bending radii as small as 1 mm [16]. Inorganic–organic hybrids, such as metal–oxide–polymer substrates, are used in bio-integrated systems like prosthetics, allowing high-density device integration. Key challenges include nanomaterial detachment under cyclic strain after 10,000 cycles and high production costs ($50–100/kg) due to complex dispersion processes. Recent innovations target improved nanomaterial adhesion through surface functionalization, though achieving large-scale, cost-effective production remains difficult.

3.4. Comparison of Substrate Materials

As a comprehensive review, the properties of various substrates are compiled in Table 1 to compare stretchability, tensile strength, electrical performance, and applications, helping guide material selection for stretchable electronics. Polymers such as PDMS and PU achieve high stretchability (150–200%) and are relatively inexpensive ($10–20/kg), making them well-suited for wearable sensors and biomedical implants. However, their inherently low conductivity requires conductive fillers like CNTs or metal particles, which can reduce flexibility and increase fabrication complexity by 20–30% due to added processing steps. Organic substrates, such as cellulose and silk, offer biodegradability within 30 days and moderate tensile strength (3–7 MPa), making them ideal for green electronics and implantable devices. Still, their limited stretchability (10–100%) and sensitivity to environmental factors like humidity limit their suitability for high-strain applications such as soft robotics. Hybrid substrates, including graphene–PDMS and AgNW–PDMS, provide excellent conductivity (<10 Ω/sq) and moderate stretchability (100–120%), making them attractive for conductive circuits and display applications. However, they face challenges such as nanomaterial detachment after 10,000 cycles and high costs ($50–100/kg) due to complex dispersion techniques. Ultimately, substrate choice depends on application-specific needs, biocompatibility for implants, transparency for displays, durability for wearables, or sustainability for eco-friendly electronics.

Figure 1 visualizes these property distributions, illustrating trade-offs among stretchability, tensile strength, conductivity, and biocompatibility to support informed material selection.

Table 1. Comparison of Flexible Substrate Materials

Material	Stretchability (%)	Tensile Strength (MPa)	Conductivity	Applications
PDMS	150	0.5–2	Low (with fillers)	Wearable sensors, e-skin
PU	>200	10	Low (with fillers)	Biomedical implants
Cellulose	10–20	5–7	Non-conductive	Green electronics
Silk	100	3–5	Non-conductive	Implantable devices
Graphene-PDMS	120	8–10	<10 Ω/sq	Stretchable circuits

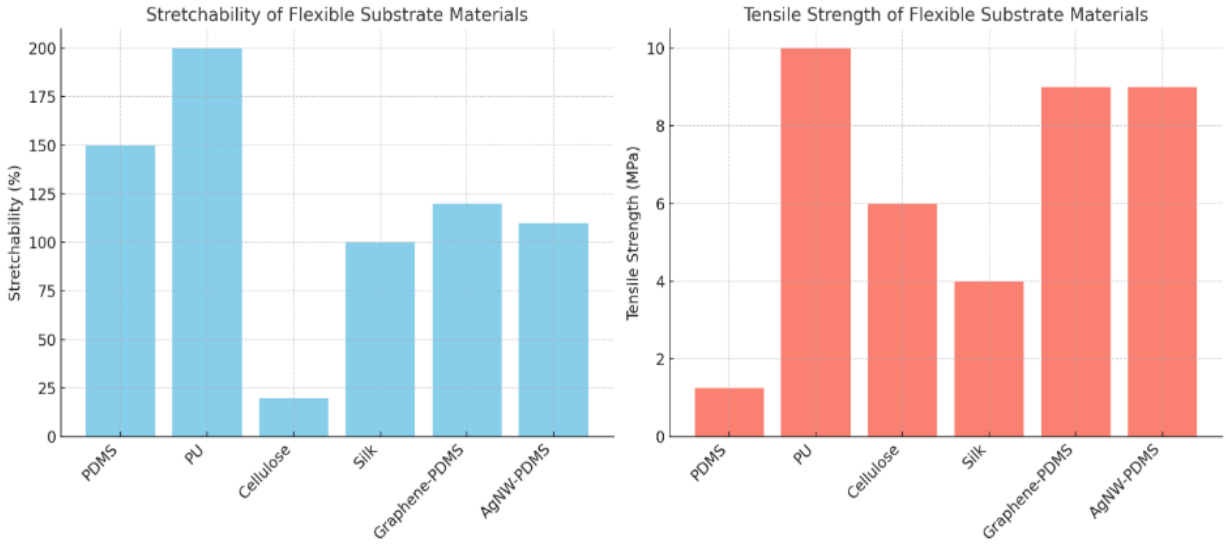


Figure 1. Distribution of Substrate Properties

4. APPLICATIONS

This requirement calls for flexible substrate materials in stretchable electronic devices, allowing them to conform to dynamic surfaces and withstand mechanical deformation. Their key characteristics such as high stretchability, biocompatibility, and electrical conductivity, enable diverse applications, including wearable electronics, biomedical devices, soft robotics, flexible displays, and emerging fields like IoT and human–machine interfaces. This section examines these applications, showing how substrates such as polydimethylsiloxane (PDMS), polyurethane (PU), cellulose, silk, and hybrid composites fulfill specific performance needs.

4.1. Wearable Electronics

Polymer substrates such as PDMS and PU are essential for wearable electronics like smart textiles, fitness trackers, and smartwatches because of their elasticity and skin-conforming comfort. PDMS-based wearable sensors, with 150% stretchability, achieve a sensitivity of 0.5 kPa^{-1} for real-time heart rate and motion monitoring, offering a rapid response time of under 0.1 s [15]. Smart textiles that integrate conductive fibers with PU substrates can endure 200% strain over 15,000 cycles, making them suitable for continuous health monitoring in sports wearables [16]. These substrates require a low Young's modulus (<2 MPa) and high cyclic durability to handle repeated deformation while preserving both user comfort and device reliability.

4.2. Biomedical Devices

Biomedical devices, such as implantable sensors and electronic skin, benefit from biocompatible substrates like silk and cellulose. Silk-based neural interfaces, with 100% stretchability and a dielectric constant of 3.5, deliver signal-to-noise ratios above 20 dB for brain signal monitoring in neural prosthetics and epilepsy diagnostics [17]. Cellulose substrates for disposable biosensors biodegrade within about 30 days under physiological conditions, making them suitable for temporary implants like glucose monitors and drug delivery systems. These materials provide tensile strengths of 3–7 MPa and high biocompatibility, ensuring safe integration with biological tissues while preserving mechanical flexibility.

4.3. Soft Robotics and Flexible Display

PDMS and hybrid composites are widely used in soft robotics and flexible displays due to their ability to handle dynamic deformation while maintaining optical transparency. Stretchable actuators made from PDMS can achieve up to 120% strain with response times under 0.5 s, enabling soft robotic grippers to perform delicate operations such as surgical manipulation. AgNW–PDMS composites have been applied in AMOLED displays, delivering ≥89% transparency and <10 Ω/sq sheet resistance, allowing foldable screens with bending radii as small as 1 mm for smartphones and wearable displays. These applications require substrates that combine high stretchability, optical clarity, and electrical conductivity to ensure consistent performance under repeated mechanical stress.

4.4. Emerging Areas

Hybrid substrates are increasingly sought after for emerging applications such as IoT and human–machine interfaces due to their superior electrical performance and scalability. Graphene–PDMS substrates have been implemented in IoT sensors, achieving low power consumption (50 μW/cm²) and high sensitivity for environmental monitoring in smart cities. Bio-integrated systems using inorganic–organic hybrids enable advanced human–machine interfaces, including prosthetics and augmented reality devices. These applications demand substrates with high conductivity and compatibility with large-scale fabrication to ensure seamless integration into smart ecosystems.

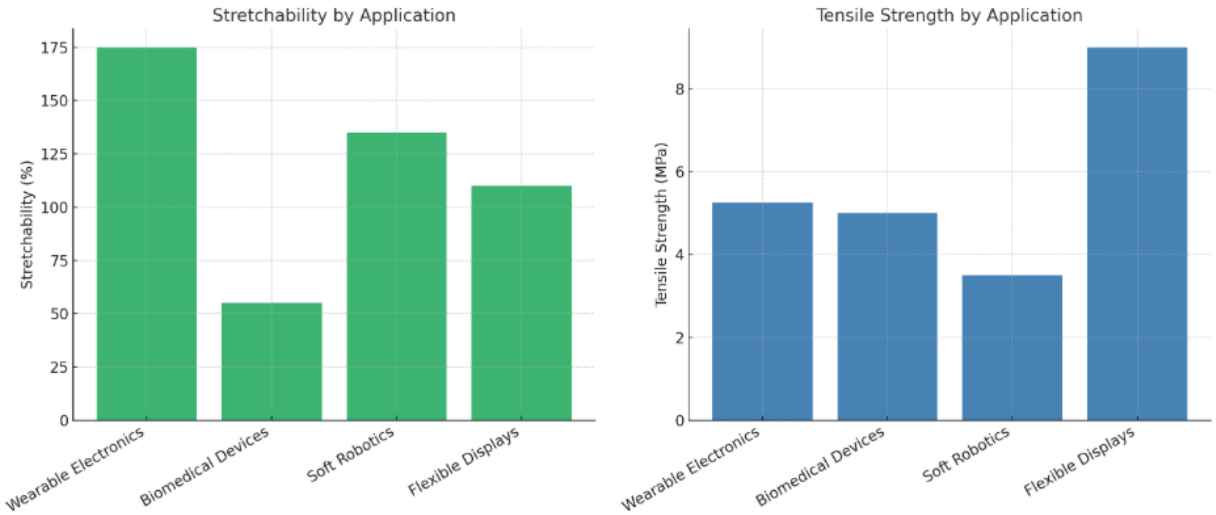


Figure 2. Graphical Representation of Stretchability and Tensile Strength

Figure 2 and Table 2 highlight the stretchability and tensile strength requirements across different applications. The chart in Figure 2 shows that wearable electronics have the highest stretchability (~150%) with moderate tensile strength, balancing comfort and durability. Biomedical devices display lower stretchability (10–100%) with moderate tensile strength, prioritizing biocompatibility. Soft robotics require similar stretchability to wearables (120–150%) but operate within a mid-range

tensile strength (2–5 MPa), which is essential for dynamic deformation. Flexible displays offer moderate stretchability (100–120%) yet stand out with higher tensile strength (8–10 MPa), emphasizing the need for transparency and conductivity.

According to Table 2, wearable electronics typically use PDMS and PU, soft robotics rely on PDMS, biomedical devices employ silk and cellulose, and flexible displays use AgNW–PDMS. The most important properties vary by application: comfort and durability for wearables, biocompatibility for biomedical devices, dynamic deformation capability for soft robotics, and optical/electrical performance for flexible displays.

Table 2. Substrate Requirements for Applications

Application	Substrate	Stretchability (%)	Tensile Strength (MPa)	Key Property
Wearable Electronics	PDMS, PU	150–200	0.5–10	Comfort, durability
Biomedical Devices	Silk, Cellulose	10–100	3–7	Biocompatibility
Soft Robotics	PDMS	120–150	2–5	Dynamic deformation
Flexible Displays	AgNW-PDMS	100–120	8–10	Transparency, conductivity

5. FABRICATION TECHNIQUES

The preparation of flexible substrate materials through effective fabrication techniques is essential for developing stretchable electronic devices that combine mechanical flexibility, electrical performance, and scalability. These methods directly shape the properties of substrates such as PDMS, PU, cellulose, and graphene-based composites, supporting applications in wearable electronics, biomedical devices, and soft robotics. This section reviews both conventional and advanced manufacturing approaches, focusing on their ability to produce substrates with high stretchability, biocompatibility, and conductivity, while also addressing recent progress and ongoing challenges.

5.1. Common Methods

Spin coating and casting are key fabrication methods for polymer and bio-based substrates. Spin coating enables the production of uniform PDMS films about 50 µm thick, offering excellent conformability and 150% stretchability, making them ideal for wearable sensors, as shown by Kim et al. [15]. By adjusting spin speeds between 1000–4000 rpm, precise thickness control is possible, although the technique is limited to small-area substrates (<100 cm^2). Casting, often used for silk and cellulose substrates, supports biocompatibility for implantable devices but requires tight process control to avoid defects like voids, which can reduce tensile strength by 15%. Screen printing is used to deposit conductive inks, such as silver, on PU substrates, achieving resolutions of around 100 µm for stretchable circuits. However, this relatively coarse resolution restricts its use in high-density interconnect applications.

5.2. Advances

Advanced fabrication methods such as 3D printing, roll-to-roll (R2R) processing, and kirigami-inspired designs improve both scalability and functionality. 3D printing has been used to create PDMS substrates with complex microfluidic channels for soft robotics, achieving 50 µm resolution and accommodating up to 120% strain. R2R processing enables large-scale manufacturing of silver nanowire (AgNW)–PDMS composites, cutting costs by 30% and delivering high transparency (≥89%) for flexible displays [14]. With throughput rates of 12 m/min, R2R is well-suited for mass production.

Kirigami-inspired cutting techniques allow otherwise non-stretchable substrates like polyimide to reach effective stretchability of 100% through patterned slits, expanding material versatility. Inkjet printing can deposit nanomaterials such as graphene onto hybrid substrates, achieving 20 μm resolution for high-performance circuits [16].

5.3. Challenges

Key fabrication challenges across different substrates include maintaining uniform thickness, achieving scalability, and ensuring cost-effectiveness. Spin coating has difficulty producing uniform layers over large areas, with thickness variations of ±12 μm across 15 cm², which can degrade electrical performance. Casting bio-based substrates such as cellulose is highly humidity-sensitive, causing variability in mechanical properties (e.g., tensile strength of 5–7 MPa). While 3D printing offers versatility, it is hindered by high material costs ($100/kg for PDMS) and slow deposition rates (1 cm³/min), making commercial deployment challenging. Roll-to-roll (R2R) processing demands precise alignment for hybrid substrates, with misalignment raising defect rates by 10%. Screen printing's coarse resolution prevents its use in sub-50 μm applications. Biomedical substrates also face regulatory barriers, with validation extending timelines by 6–12 months. Table 3 outlines these trade-offs.

Table 3. Summarizes Fabrication Techniques and their Trade-Offs

Technique	Resolution (μm)	Scalability	Cost	Applications
Spin Coating	10–50	Low	Low	Wearable sensors
Casting	50–100	Medium	Medium	Biomedical devices
3D Printing	50	Medium	High	Soft robotics
R2R Processing	100	High	Medium	Flexible displays

6. CHALLENGES AND LIMITATIONS

Over the past decade, substantial advances have been made in developing flexible substrate materials as platforms for stretchable electronic devices in areas such as wearable electronics, biomedical devices, soft robotics, and the Internet of Things (IoT). Despite this progress, persistent mechanical, electrical, environmental, and scalability challenges still impede widespread adoption and commercialization. This section analyzes these constraints in detail, drawing on recent studies (2020–2025) to identify barriers to practical implementation and guide future research directions in stretchable electronics.

6.1. Mechanical Limitations

The most critical issue here is the mechanical fatigue of flexible substrates under repeated three-dimensional strain. While high stretchability (150–200%) is advantageous, fatigue during prolonged use can degrade performance in polymer substrates such as polydimethylsiloxane (PDMS) and polyurethane (PU) [33]. PDMS develops micro-cracks after 10,000 cycles at 100% strain, leading to a 20% reduction in elasticity and compromising reliability in wearable health-monitoring sensors. PU maintains structural integrity for up to 15,000 cycles at a tensile strength of ~10 MPa but exhibits creep under sustained strain (>150%). Polyimide (PI), despite its excellent heat resistance (up to 300 °C), offers <50% stretchability, restricting its use in dynamic systems like soft robotic actuators. Traditional organic substrates such as cellulose and silk (tensile strengths 3–7 MPa) are prone to tearing under high strain (>50%). Hybrid materials like graphene–PDMS composites improve durability but still suffer from nanomaterial detachment after ~12,000 cycles, shortening lifespan by ~25%. Overcoming these challenges will require advanced material designs, such as self-healing polymers or crosslinked composites, to boost fatigue resistance and ensure long-term reliability in stretchable electronics.

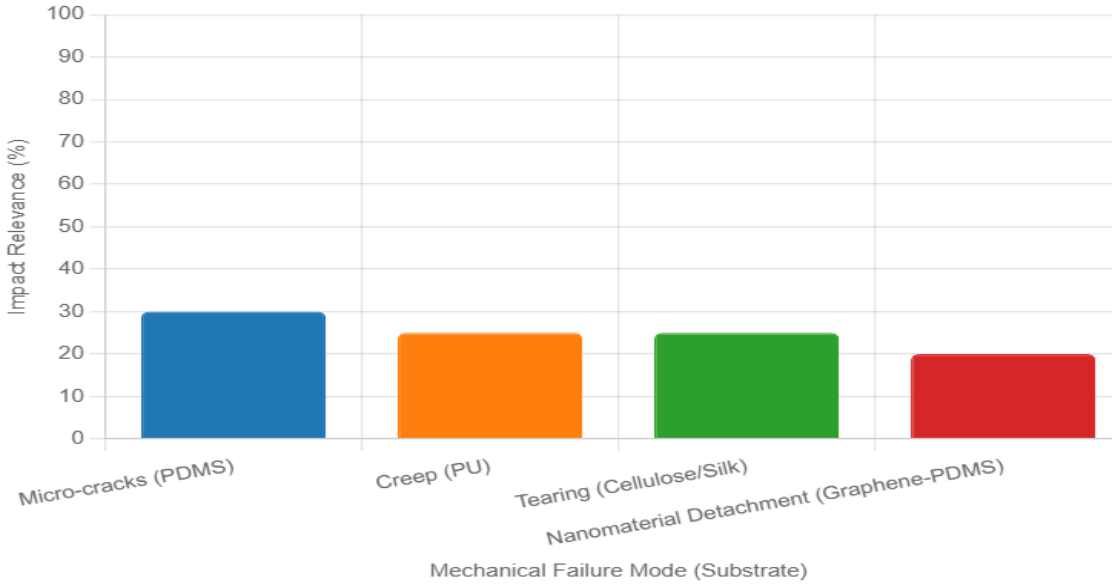


Figure 3. Impact of Mechanical Failure Modes on Flexible Substrates

Fig 03 shows the relative impact (in %) of four key mechanical failure modes, micro-cracks (PDMS), creep (PU), tearing (cellulose/silk), and nanomaterial detachment (graphene-PDMS), on substrate performance in stretchable electronics. Micro-cracks have the highest impact (30%), followed by creep and tearing (25% each), and nanomaterial detachment (20%). The chart highlights how these failures affect reliability in applications like wearables and biomedical devices.

6.2. Electrical Performance

Stretchable electronics must maintain electrical conductivity under mechanical deformation, yet polymer and organic substrates typically require conductive fillers, making stable performance difficult to achieve. Graphene–PDMS composites can sustain sheet resistance below 10 Ω/sq at up to 120% strain, but their performance declines after more than 10,000 cycles. In flexible displays, silver nanowire (AgNW)–polymer composites offer high transparency (≥89%) but lose conductivity with repeated bending.

6.3. Environmental and Cost Considerations

Cost and environmental sustainability remain major obstacles to scaling stretchable electronics with flexible substrates. While polymer materials like PDMS and PU provide excellent mechanical properties, their large-scale production relies on nonrenewable petroleum resources and generates non-biodegradable waste, raising environmental costs. Bio-based substrates such as cellulose and silk are fully biodegradable within 30 days and environmentally friendly, but their production costs $50–100/kg are much higher than conventional polymers at $10–20/kg. Hybrid materials, including graphene and silver nanowire composites, are even more expensive, costing $50–100/kg due to complex nanomaterial synthesis and dispersion processes. Manufacturing methods also affect cost efficiency: roll-to-roll processing can reduce expenses by 30%, but ensuring uniform nanomaterial dispersion adds complexity and requires costly equipment. Biomedical applications face additional challenges, with FDA approval extending timelines by 6–12 months and necessitating extensive biocompatibility testing, adding $500,000–$1 million to development costs. The environmental impact is worsened by energy-intensive fabrication methods, with 3D printing consuming 2–3 times more energy than traditional casting. These combined environmental and economic pressures highlight the urgent need for affordable, sustainable production methods and biodegradable, high-performance materials that meet regulatory requirements and satisfy growing consumer demand for green technology.

6.4. Scalability and Commercialization

Scaling up production for commercial applications remains challenging. Roll-to-roll (R2R) processing, while scalable, struggles with uniform thickness for hybrid substrates. 3D printing offers customization but is cost-prohibitive for mass production ($100/kg for PDMS).

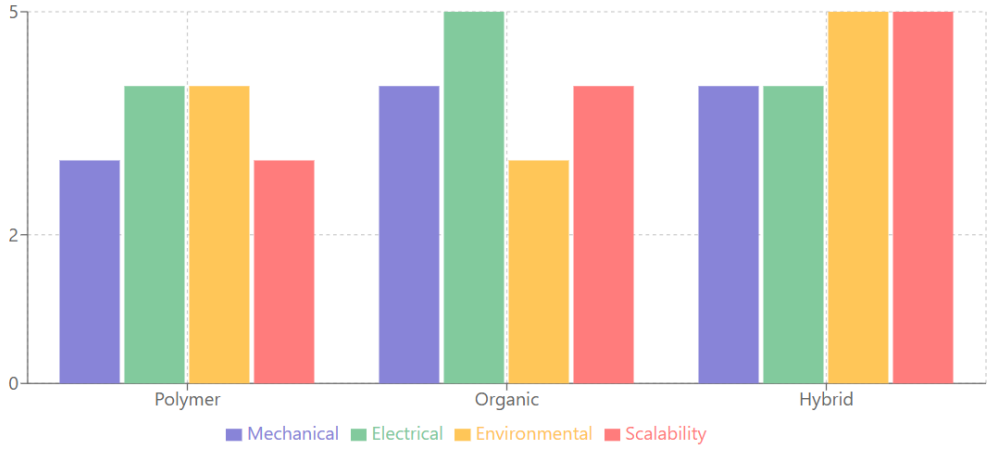


Figure 4. Challenge Severity Comparison Across Polymer, Organic, and Hybrid Substrates

Table 4. Challenges Across Substrate Types

Substrate Type	Mechanical Challenge	Electrical Challenge	Environmental/ Cost Issue	Scalability Issue
Polymer (PDMS, PU)	Fatigue after 10,000 cycles	Conductivity loss with fillers	Non-renewable resources	Uniformity in R2R
Organic (Cellulose, Silk)	Tearing at high strain	Non-conductive	High processing cost	Limited raw material
Hybrid (Graphene-PDMS)	Nanomaterial detachment	Conductivity degradation	High nanomaterial cost	Complex dispersion

Table 4 represents the Challenges across substrate types. While Fig 4 Illustrates a clustered bar chart comparing the severity of challenges across three categories of substrates: Polymer (PDMS, PU), Organic (Cellulose, Silk), and Hybrid (Graphene–PDMS). The graph rates each substrate on a 1–5 scale (1 = minimal challenges, 5 = severe challenges) for four key challenge categories, mechanical, electrical, environmental, and scalability. This visualization highlights the variation in challenges faced by each substrate type, offering a basis for evaluating trade-offs between material properties and their practical use in commercial applications.

7. CONCLUSION

An in-depth review has been provided regarding flexible substrate materials for stretchable electronic devices and their importance to the progress of state-of-the-art applications in wearable electronics, biomedical devices, soft robotics, and IoT. This paper provides a comprehensive review on the progress of flexible electronics in the past decade by summarizing substrate materials and their fabrication techniques and challenges, covering several types of substrates including polymer-based, organic, bio-based, and hybrid and discussing how these advances will play a critical role towards shaping the future of flexible electronics.

Polymer substrates, such as polydimethylsiloxane (PDMS) and polyurethane (PU), have emerged as the state-of-the-art stretchable electronics due to excellent stretchability (150 ~ 200%) and

biocompatibility for wearable sensors and biomedical implants [4]. PDMS, possessing a Young's modulus of 0.5 to 2 MPa, is advantageous for highly sensitive electronic skin applications (<1 kPa^{-1}) while PU exhibits a tensile strength of ~10 MPa that may find broad utility in dynamic functional environments. While polyimide (<50% stretch) is less elastic, its thermal stability makes it an excellent candidate for flexible displays. Continued attention is given to organic and bio-based substrates, including cellulose59 and silk60 for their sustainability. Green alternatives for cellulose, degrading within 30 days, could act as temporary biological sensors and silk serves as a neural interface with a dielectric constant of 3.5, beneficial for applications in brain signal monitoring and medical diagnostics. For stretchable circuits and AMOLED displays, both of these hybrid substrates: graphene-PDMS and silver nanowire (AgNW)-PDMS mixtures, provide high transparency (≥89%) with the low sheet resistance (<10 Ω/sq).

It further discusses the advancement in fabrication methods like spin coating, casting and 3D printing, and roll-to-roll (R2R) processing for substrate manufacturing. Spin coating provides uniform PDMS films (50 μm), while 3D printing allows fabrication of complex geometries needed to soft robotics. This was followed by increases in the number of printing steps (203) and vacancies required transformation from R2R processing improving scalability and reducing costs to alternatives by up to 30% but increasing challenges in hybrid substrate homogeneity control. The benefit of kirigami-inspired designs is that materials previously limited in use (like non-stretchable substrates) can leverage flexibility-extension mode devices.

However, these developments are still beset by problems of mechanical fatigue (as evidenced by PDMS cracking after 10000 cycles), loss in conductance under strain and high processing cost ($50–100/kg for organic substrates). On top of that, there was also a major question surrounding biocompatibility and certifications which make adopting the bendy substrate in commercial biomedical applications an even greater challenge.
The advantage of this review is that it provides a comprehensive, unified report on flexible substrates, bridging the gaps in previous literature where only specific types of active components in stretchable electronics were targeted. We underscore these fundamental trade-offs that exist between stretchability, durability and sustainability, providing a grounding for the selection and development of materials in the future. These results not only highlight the promise of stretchable electronics for applications in areas such as health care, robotics and Internet of Things (IoT), but also help to identify key bottlenecks that need to be hurdled in order for advanced technologies like these to be commercialized in full swing.

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